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RESEARCH MEMORANDUM

FLIGHT MEASUREMENTS OF THE VIBRATORY BENDING AND TORSION STRESS ON A SUPERSONIC-TYPE PROPELLER FOR FLIGHT MACH NUMBERS UP TO 0.95

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FLIGHT MEASUREMENTS OF THE VIBRATORY BENDING AND TORSION STRESS ON A SUPERSONIC-TYPE PROPELLER FOR FLIGHT MACH NUMBERS UP TO 0.95

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SUMMARY

Vibratory stress measurements were obtained in flight on a supersonic-type propeller for forward Mach numbers up to 0.95.

The magnitude of the vibratory bending stress was low throughout the flight range of the test airplane. Vibratory bending stress was almost pure once-per-revolution stress (1-P) for flight Mach numbers up to approximately 0.82. Above this Mach number the wave shape broke down until at a Mach number of 0.90 the shape was rather complex.

An electrical frequency analysis of a vibratory bending record at a Mach number of 0.90 indicated that the primary response was at 1-P frequency (59 cps). A relatively large response was indicated at 75 cps which was thought to be the first natural bending frequency of the blade.

A maximum vibratory bending stress of ±11,500 pounds per square inch was measured during an air start of the engine at 250 miles per hour at an altitude of 5,000 feet. The stress peaked very rapidly at approximately 750 rpm and decreased to ±4,000 pounds per square inch in about 3 seconds time, or by the time the rotational speed was stabilized at 1,000 rpm preparatory to firing the engine.

The vibratory torsional stress did not exceed ±2,000 pounds per square inch. There was no evidence of flutter throughout the flight investigation.

INTRODUCTION

The supersonic propeller is characterized by the fact that all sections operate at supersonic resultant Mach numbers. These high Mach

numbers require the use of thin blades to attain good values of propeller efficiency. Thin blades, however, focus attention on the vibratory-stress characteristics of the propeller.

The vibratory stresses of major importance are the 1-P and stall flutter stresses. The 1-P stress is the stress that occurs once per revolution due to the oscillating aerodynamic load imposed on the propeller as a result of inclination of the thrust axis (See refs. 1 and 2.) The use of thin blade sections results in a more flexible blade, which in turn lowers the natural bending frequency to a value closer to the operating rotational speed with attendant magnification of the 1-P stress. Since supersonic-type propellers have thin flexible blades with low values of torsional frequency, they are more susceptible to stall flutter. (See ref. 3.)

This paper presents flight measurements of the vibratory bending and torsion stresses for a supersonic-type propeller, which are indicative of the 1-P and flutter stresses. Results are presented for level-flight conditions at altitudes of 20,000 and 30,000 feet and forward Mach numbers up to 0.95.

The propeller blades are considered, on the basis of existing knowledge, to represent the best compromise between aerodynamic and structural considerations. This propeller is the first of a series of supersonic-type propellers to be studied in a joint NACA, Air Force, and Navy program as described in reference 4.

SYMBOLS

A	local angle of inclination of thrust axis at propeller plane
b	blade chord, ft
D	propeller diameter, ft
h	blade thickness, ft
M	free-stream Mach number
M_x	blade-section Mach number at design forward Mach number of 0.95
q	dynamic pressure, lb/sq ft
x	radial location, percent radius
β	blade angle, deg.

EQUIPMENT

The propeller was a three-blade configuration of 7.2-foot diameter, designed for a forward Mach number of 0.95, advance ratio 2.2, and power coefficient of 0.26. The blades are made of solid steel (SAE 4340) having an ultimate tensile strength of 180,000 pounds per square inch. The blade is composed of NACA 16-series symmetrical airfoil sections, and the plan form is tapered from an 11.1-inch chord at the spinner surface to an 8.4-inch chord at the tip, while thickness varies from 4 percent to 2 percent of the chord. The blade-form curves are shown in figure 1.

The propeller was tested in conjunction with a "spherical" spinner. (See fig. 2.) The spinner contour is a 17.5-inch radius sphere fairing into a 60° included-angle conical nose section. This type of spinner, in which the contour of the blade-spinner juncture is spherical, is used to obtain a mechanically simple blade-spinner seal and to maintain a constant juncture geometry under all conditions of operation.

The propeller flight test vehicle is the McDonnel XF-88B airplane which was modified by the addition of a turboprop engine in the nose. General specifications of the airplane can be found in reference 4. The turboprop drives the propeller at 3,500 rpm.

INSTRUMENTATION

Determination of Stress

One of the propeller blades was instrumented with two strain-gage bridges (fig. 3) for measuring vibratory bending strain and one bridge for vibratory torsion strain. The gages were located on the blade center line; bending gages at 37.0 and 39.4 percent radius and the torsion gage at 78.7 percent radius as noted in table I. The gages were located so as to bracket the positions of maximum vibratory stress calculated in reference 5.

Each strain-measurement location consisted of a four-component strain-gage bridge. Four gages were used to increase sensitivity, cancel centrifugal strains, and cancel temperature effects. The output of the strain-gage bridges was recorded on a Consolidated oscillograph. The galvanometers used to record bending strain had a natural frequency of 150 cps; the natural frequency for the torsion gage was 200 cps.

Determination of Aq

The Aq factor, or the local angle of inclination of the thrust axis at the propeller plane times the dynamic pressure, was determined during flight tests without a propeller installed. (See ref. 6.) The local angle of inclination A was determined from a differential-pressure measurement between a pair of diametrically opposite orifices located in the vertical plane on the nose of a dummy nonrotating spinner. The magnitude of the angle was computed from the differential-pressure measurement divided by the product of airplane impact pressure and a constant. The constant used in determination of angle was obtained from a wind-tunnel calibration of a cone with the same included angle as the spinner. Angle determination is considered accurate to $\pm 0.2^{\circ}$.

General Airplane Instrumentation

The source of static and total pressure for the airspeed system was a Kollsman type 651 pitot-static head, mounted 1 tip chord length ahead of the wing tip of the airplane. The impact pressure and static pressure were recorded with a standard NACA airspeed recorder. The Mach number was determined from a radar calibration to be accurate within ± 0.005 for Mach numbers reported on herein.

TESTS AND PROCEDURE

Strain-gage records were obtained during engine starts at 5,000 feet and level flight at 20,000 and 30,000 feet. For the engine starts, the records were turned on while the propeller was feathered and remained on until the propeller was operating at flight idle rotational speed (2,750 rpm). The level-flight records were obtained during acceleration to maximum Mach number by increased main-jet power and afterburner operation. The power coefficient during the tests varied from 0.19 to 0.23, the thrust coefficient varied from 0.10 to 0.08, and the advance ratio ranged up to 2.2.

The maximum stress values were determined from visual inspection of the strain-gage records simply by reading a succession of maximum amplitudes throughout the record length. The records were approximately 2 minutes in length and were run at 15 inches per second.

RESULTS AND DISCUSSION

Vibratory Bending Stress

Bending data were obtained at two radial locations shown in table 1. The stress determined from strain measurements at 39.4 percent radius was found to be the maximum of the two measurements.

Stress measurements in level flight.- Three typical examples of the wave shape of the vibratory bending stress are presented in figure 4. The records were obtained in essentially level flight at approximately 30,000 feet. The first example (fig. 4(a)) is representative of the wave shape existing for Mach numbers up to 0.82. This example is mainly a pure 1-P wave shape. The example in figure 4(b) is the type of wave shape present in the Mach number range from 0.82 to 0.90. Although the shape is primarily 1-P there is evidence that some other frequencies are present. This breakdown in the wave shape occurs in the Mach number range where separation of the flow off the spherical spinner was noted in the spinner investigation of reference 6. The wave shape in figure 4(c) occurs at Mach numbers between 0.90 and 0.92. Here the wave shape has become a complex one consisting of one or more frequencies other than 1-P.

The measured vibratory bending stress for two level-flight speed runs are presented as a function of Mach number in figure 5. One run covers a Mach number range from 0.65 to 0.85 at approximately 20,000 feet and the other is for a Mach number range from 0.78 to 0.92 at 30,000 feet. The values of stress represent the maximum amplitude, as measured from the mean line, of the vibratory bending stress for each given condition. The excitation factor Aq, the product of the inclination of the propeller and dynamic pressure, corresponding to the flight conditions for which the stress was measured is also shown in figure 5. The angle A is the local inclination of the thrust axis and, as a result, the Aq determination does not include the effect of induced angle at radial locations along the blade. The Aq calculations of reference 5 are based on an estimate of the same A measured in this investigation.

It is believed that the loading per Aq does not change much over the range of conditions shown in figure 5 so that the stress per Aq should be constant. This is substantially true below $M = 0.82$ and the stress per Aq is about 5.0, which compares with a calculated value of 6.5 in reference 5. Above $M = 0.82$ the maximum amplitude shown is no longer a measure of the pure 1-P bending stress because of the existence of other vibration frequencies, as pointed out in figure 4. The erratic nature of the variation of A with Mach number is a result of some loss of altitude and variation of normal acceleration during the flight maneuver.

Resonance diagram. - A resonance diagram will be useful for interpretation of the vibratory characteristics of the propeller. A simple approximate plot of the first natural bending frequency showing the first and second propeller orders of rotation as a function of rotational frequency is presented in figure 6. This figure is constructed from knowledge of the first static natural bending frequency (18 cps) and the critical speed (approximately 170 cps). The static bending frequency was determined from ground shaking of the blade and the critical speed was given in reference 5. The diagram indicates a resonance condition at low rotational speed; intersection of second-order excitation (2-P) and the first bending frequency. The operating conditions for the propeller should show primary response to 1-P excitation with no resonance condition likely.

Frequency analysis.- In an effort to determine the nature of the complex wave shape occurring in the Mach number range from 0.90 to 0.92, a frequency analysis was performed on a 4-second interval of record by using the electrical frequency analyzer equipment of reference 7.

The galvanometer trace was manually transcribed on a magnetic tape in four intervals and spliced together to form a continuous loop. The loop was played through an analyzer having a 4-cps-band-width filter. The filter was continuously adjusted over a frequency range up to 120 cps. Any frequency components in the data which fell within the filter's pass band were passed by the filter, squared, averaged, and then applied to a direct-writing recorder. The result of this analysis is shown in figure 7 in the form of a power spectral density with units of $(\text{lb/sq in.})^2/\text{cps}$. The maximum power present in the record occurs at 59 cps and is judged from figure 6 to be the response of the blade to 1-P excitation. The relatively large power present in the record at 75 cps is thought to be the response of the blade at its first natural rotating frequency. The low power level present at 118 cps indicates that there is little response to 2-P excitation.

The relatively large power present at 75 cps indicated the need for further analysis to shed some light on the nature of this response. The further analysis was in the form of an amplitude time history, performed with the analyzer equipment, at 59 cps and 75 cps. In this case, the filter output was recorded directly with a galvanometer element bypassing the squaring element of the analyzer. The time histories are distorted by the time constants of the recorder and of the filter. The overall time constant is of the order of 0.3 second and, thus, variations which occurred much faster than this rate would not be shown. The effect, then, is that the actual component time history is subjected to a running average having an averaging period of about 0.3 second.

The envelope of time history of the stress, in the sample record, at 59 and 75 cps is presented in figure 8. The sharp decrease in amplitude seen in the record results from the four splices that were made in the record to make a continuous loop. It should be noted that the time histories as made could not be correlated with absolute flight record time nor with each other.

The amplitude of the 1-P stress at 59 cps indicates a stress level that varies in a fairly smooth manner from a maximum of ±1,260 pounds per square inch to a minimum of ±860 pounds per square inch. The variation is the same order of magnitude as the variation of Aq during the time of the sample record showing the overall variation of stress with Aq to be approximately 5.0. The amplitude variation at 75 cps appears to be random with time. The presence of the four splices can be seen again in this record. The stress varies randomly from a minimum of 130 pounds per square inch to a maximum of 950 pounds per square inch. The amplitude variation at 75 cps is thought to be the response of the blade at its natural bending frequency. Although the source of excitation is unknown there are a number of factors which might influence it. The inboard portion of the blade is in a region of flow separation off the spinner. The airplane is being subjected to a mild form of buffeting (ref. 6) which is a result of the flow separation off the spinner. It is thought that one or more of these conditions results in a random excitation which excites the blade natural frequency.

Engine start condition.- A time history of the vibratory bending stress and rotational speed during an air start of the engine is presented in figure 9. The start occurred at a 5,000-foot altitude at an airspeed of 250 miles per hour. This condition resulted in the maximum vibratory bending stress obtained during the flight test program. The high momentary stress at 25 seconds occurs during the time the propeller is windmilling and accelerating the engine to starting speed. There was no measure of the blade angle during start; however, it is known from the starting sequence that the peak stress is occurring at a blade angle somewhat lower than the set starting blade angle of 53°. The high stress level is thought to be a result of twice-per-revolution (2-P) resonance in the first mode. The wave shape of the stress record indicates a strong 2-P component on top of the basic 1-P. The 2-P component appears and the overall stress builds up rapidly to a peak (at approximately 750 rpm) and decreases equally fast as the 2-P component disappears. The leveling off of the rotational speed and stress for some 30 seconds occurs while the engine control system is firing the engine with resulting constant excitation, rotational speed, and blade angle. The rapid rise in rotational speed at 50 seconds indicates that the engine has started, and the rotational speed rises until flight idle rotational speed is attained (2,750 rpm). The momentary decrease in stress during this time is due to the airplane trim change, and corresponding change in 1-P excitation, that occurs during an air start of a propeller-engine combination.

A check on the vibratory bending stresses that the propeller might be subjected to through the normal flight test range of the McDonnell XF-88B airplane can be estimated from figure 10. This figure presents the variation of Aq with Mach number for the range of altitude and maneuver load factors that the airplane is normally operated through. The angle of inclination of the thrust axis was not determined for Mach numbers below 0.6. Use of the experimentally determined 1-P stress per Aq of 5.0 indicates the stress. The maximum excitation factor that could be expected with the McDonnell XF-88B airplane would be 1,500 pounds per square foot at a maneuver load factor of 2.0g at 30,000 feet and a Mach number of 0.6. The resulting 1-P stress would be 7,500 pounds per square inch.

For the flight conditions chosen, the vibratory bending stress would be practically all 1-P. The choice of a higher Mach number condition would have resulted in a lower 1-P stress with a rather large stress resulting from a random aerodynamic excitation. However, this combined stress would seem to be lower than the pure 1-P stress the propeller would feel at the lower Mach number. This condition results in the maximum stress except for the high momentary stress occurring during air start of the turboprop engine.

The bending stresses encountered in this installation are low in relation to the strength of the material. The steel has an ultimate tensile strength of 180,000 pounds per square inch and a working endurance limit of ±56,000 pounds per square inch.

The low level of the vibratory bending stress results from the high value of the ratio of hub to tip radius combined with the attendant stiffening due to the high rotational speed and from the low level of 1-P excitation. The hub-to-tip ratio of 0.25, which may be considered as the effective hinge point of the blade, is somewhat outboard of the 25-percent radial station. In contrast to other propeller installations such as those found on transports, bombers, and long-range fighters, the McDonnell XF-88B, as investigated by the NACA, experiences a small change in wing loading. The resulting change in inclination of the thrust axis is restricted to a range of less than 2°.

Vibratory Torsion Stress

The propeller was predicted by the calculations of reference 5 and by whirl tests to be free of flutter throughout the operational range of the McDonnell XF-88B airplane. These predictions were borne out by the flight test program. Torsional stress data were obtained from the strain measurement at the 78.7-percent radial location (table I). The maximum vibratory torsion stress is presented as a function of Mach

number in figure 11. The highest stress attained was ±2,000 pounds per square inch during an emergency propeller feather operation at $M = 0.95$. Aside from this case the stress level varied from ±500 pounds per square inch at low Mach number to ±1,500 pounds per square inch at Mach number 0.95. The multiplicity of points below $M = 0.90$ is indicative of the variation of stress level under essentially constant conditions. The variation at $M = 0.95$ shows the decrease in stress as the propeller is feathered. Visual inspection of the torsion records at rated rotational speed (3,500 rpm) indicated that a frequency of 165 cps was present which is reasonably close to the experimentally determined static natural torsion frequency of 151 cps and the calculated (ref. 5) static frequency of 144.7 cps. There was no evidence of flutter during the entire flight program.

Ground static operation of the propeller at approximately 1,800 horsepower with a blade angle of 15° (at 0.75r) resulted in a maximum vibratory torsion stress of only 670 pounds per square inch. Whirl tests of the propeller indicated that maximum power (2,500 horsepower) could be absorbed statically without encountering stall flutter.

CONCLUSIONS

Vibratory stress measurements obtained in flight on a supersonic-type propeller, for forward Mach numbers up to 0.95, indicate the following results:

1. The magnitude of the vibratory bending stress was low throughout the flight range of the test airplane.

2. Vibratory bending stress was almost pure once-per-revolution stress (1-P) for flight Mach numbers up to approximately 0.82. Above this Mach number the wave shape broke down until at a Mach number of 0.90 the shape was rather complex.

3. An electrical frequency analysis of vibratory bending record at a Mach number of 0.90 indicated that the primary response was at 1-P frequency (59 cps). A relatively large response was indicated at 75 cps which was thought to be the first natural bending frequency of the blade.

4. A maximum vibratory bending stress of ±11,500 pounds per square inch was measured during an air start of the engine at 250 miles per hour at an altitude of 5,000 feet. The stress peaked very rapidly at approximately 750 rpm and decreased to ±4,000 pounds per square inch in about 3 seconds time, or by the time the rotational speed was stabilized at 1,000 rpm preparatory to firing of the engine.

5. The vibratory torsional stress did not exceed ±2,000 pounds per square inch. There was no evidence of flutter throughout the flight investigation.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 4, 1956.

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2. Rogallo, Vernon L., Roberts, John C., and Oldaker, Merritt R.: Vibratory Stresses in Propellers Operating in the Flow Field of a Wing-Nacelle-Fuselage Combination. NACA TN 2308, 1951.

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4. Hammack, Jerome B., and O'Bryan, Thomas C.: Flight Measurements of Section Efficiency, Thrust, and Power of a Supersonic-Type Propeller at Mach Numbers to 0.9. NACA RM L55I21, 1956.

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TABLE I.- STRAIN-GAGE LOCATIONS

Radial location, percent radius	Radius, in.	Gage type
37.0	16.0	Bending
39.4	17.0	Bending
78.7	34.0	Torsion

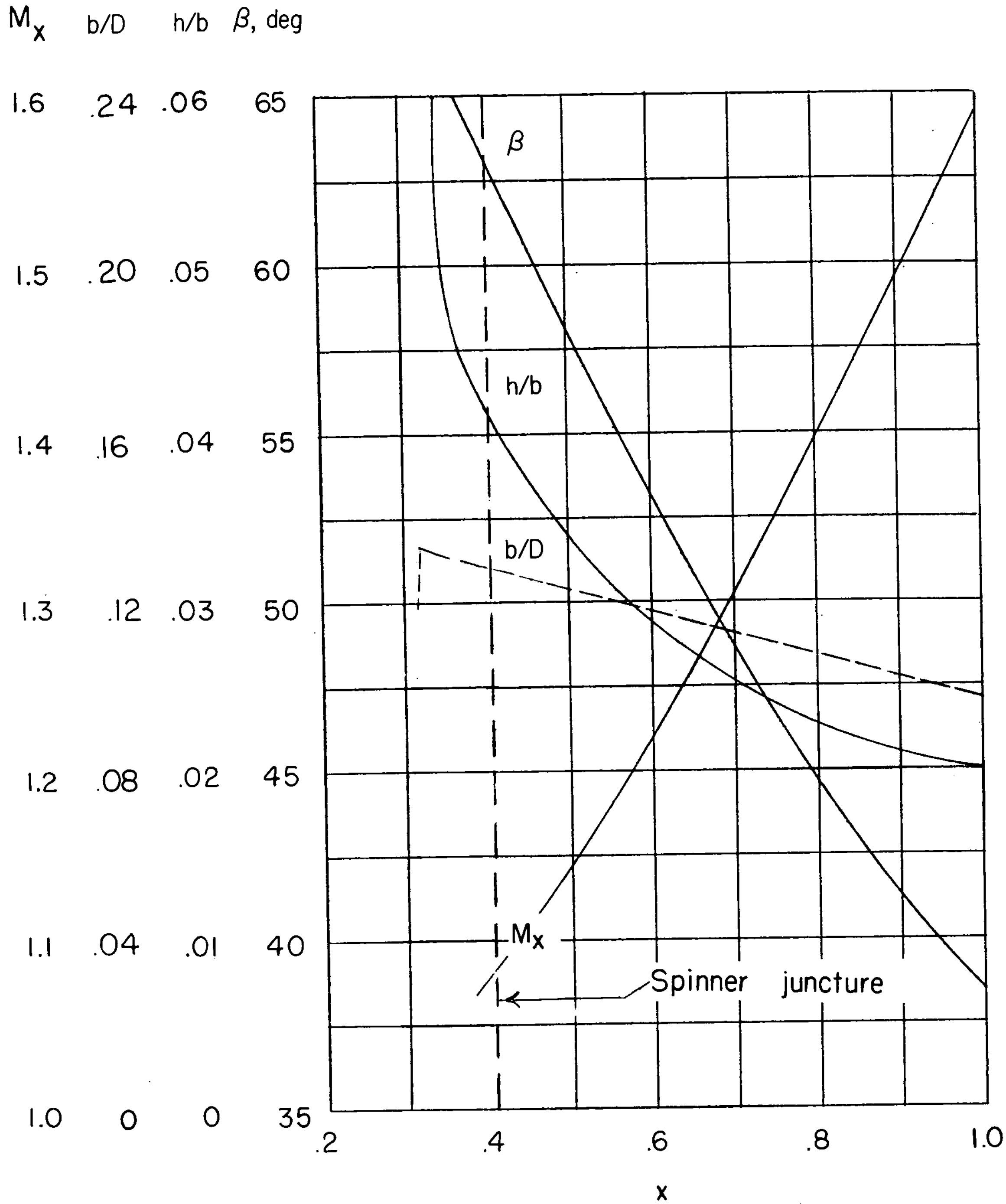

Figure 1.- Blade-form curves for 7.2-foot supersonic-type propeller.

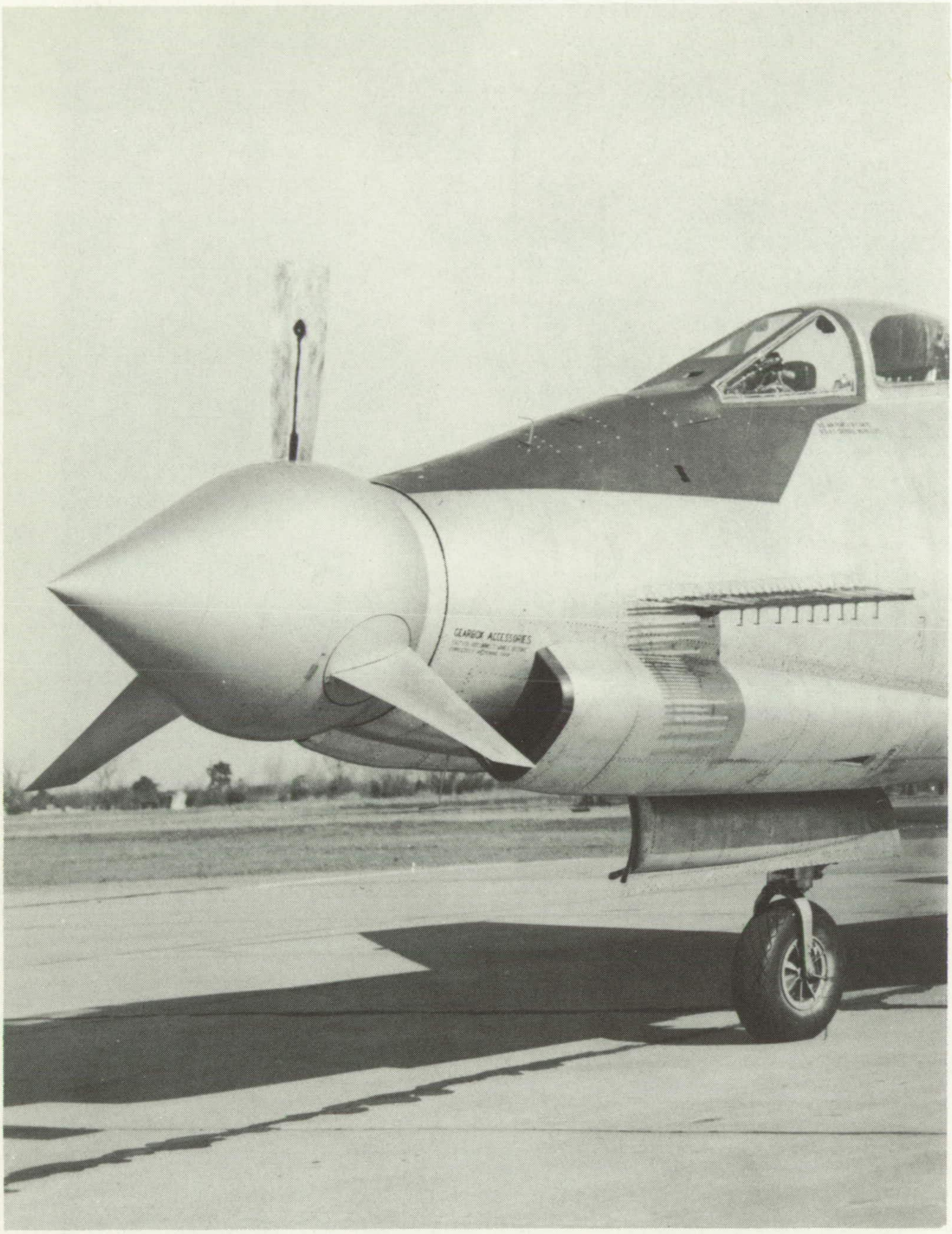

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Figure 2.- Photograph of supersonic-type propeller and spherical spinner installed on test airplane.

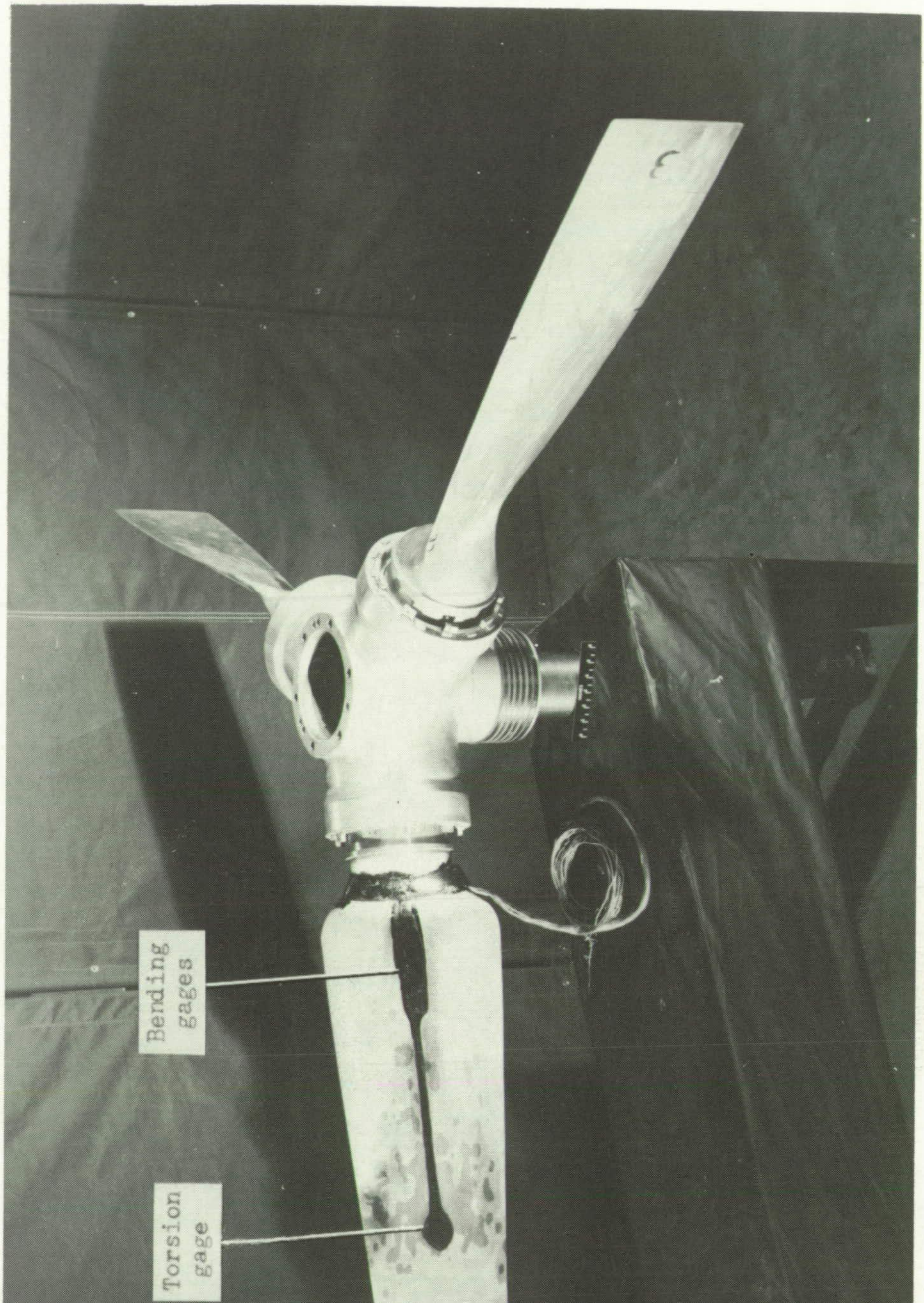

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Figure 3.- Photograph of supersonic propeller with strain gages installed.

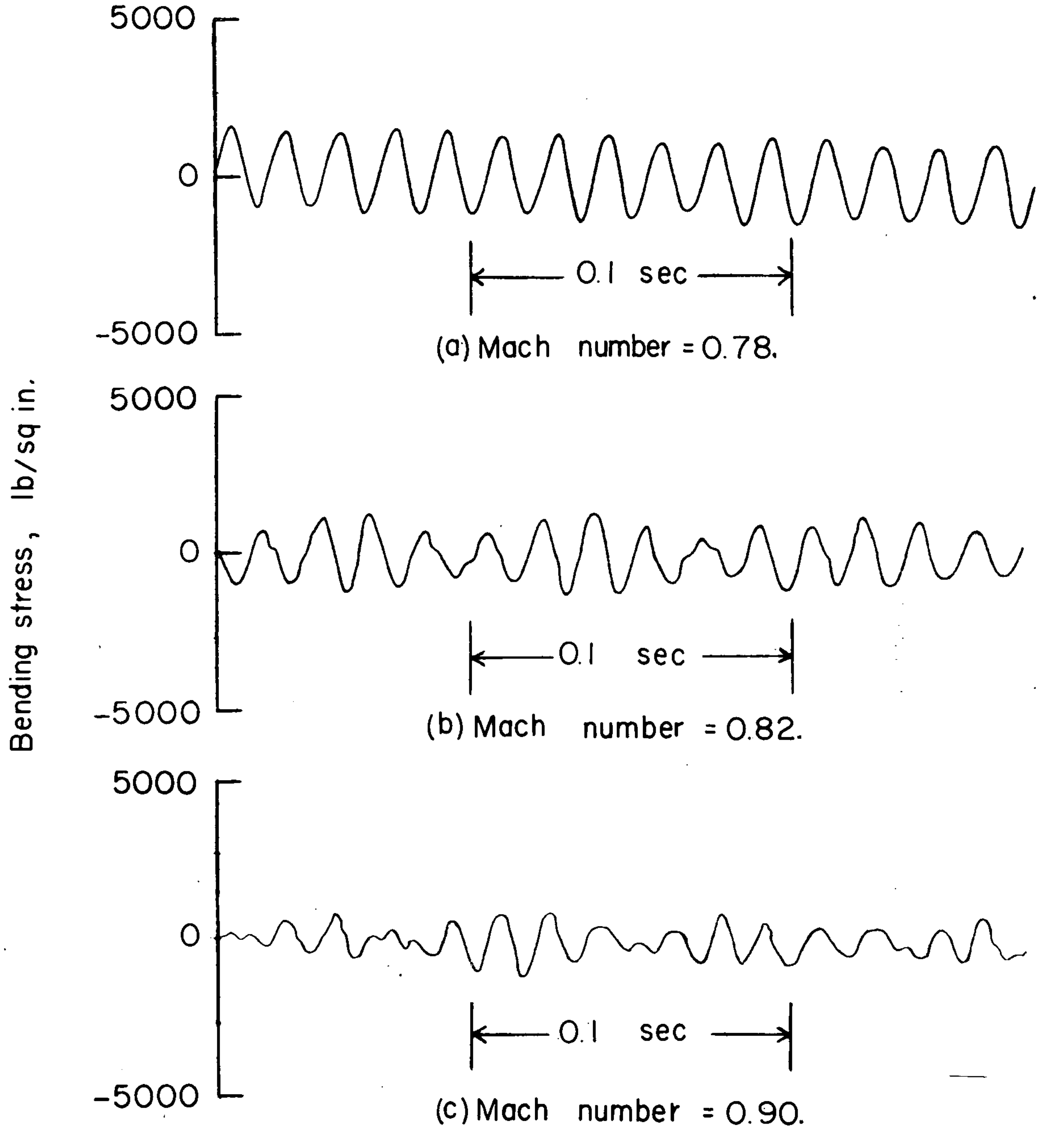

Figure 4.- Typical examples of wave shape of vibratory bending stress.

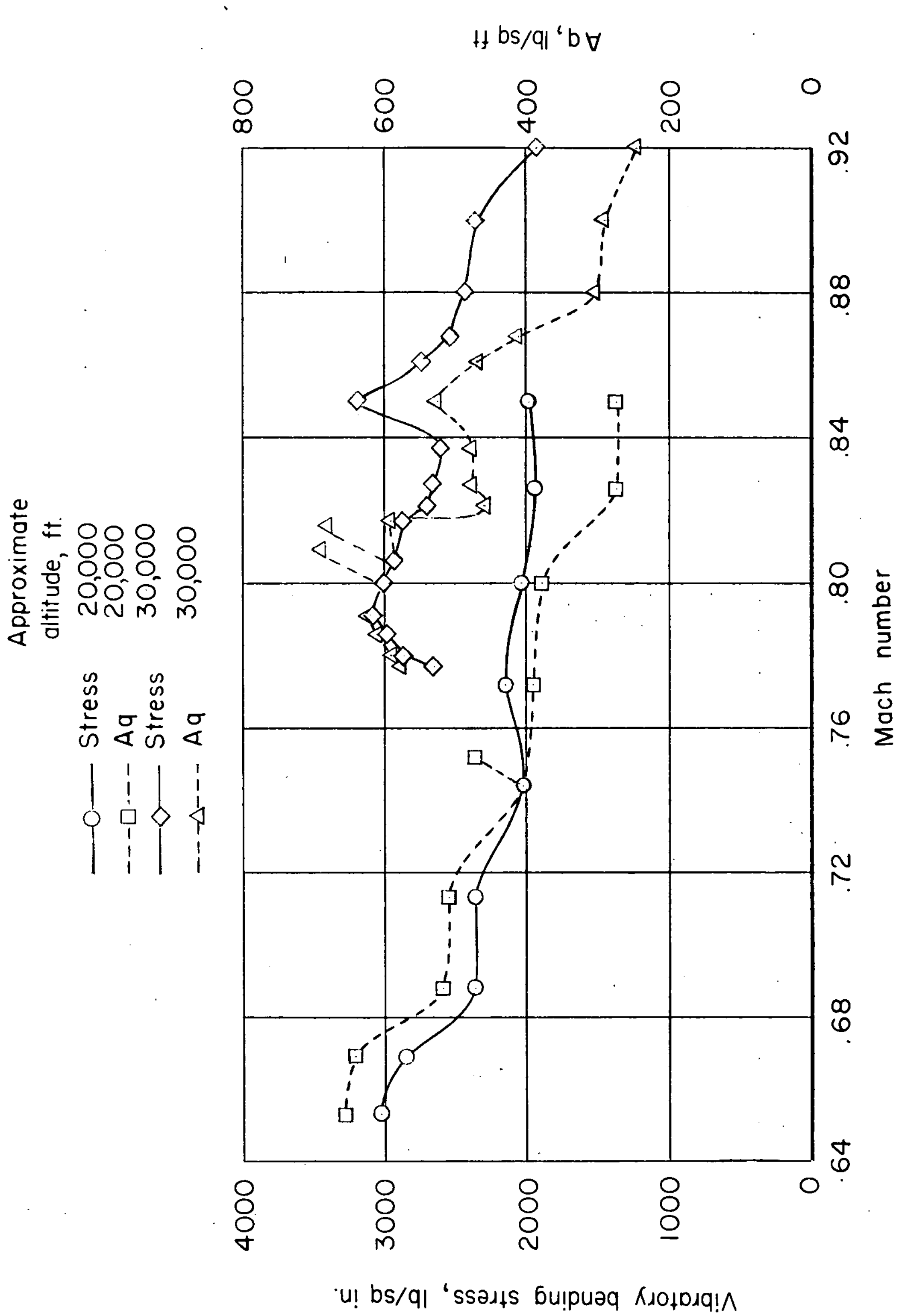

Figure 5.- Maximum vibratory stress and Aq for Mach numbers from 0.65 to 0.92.

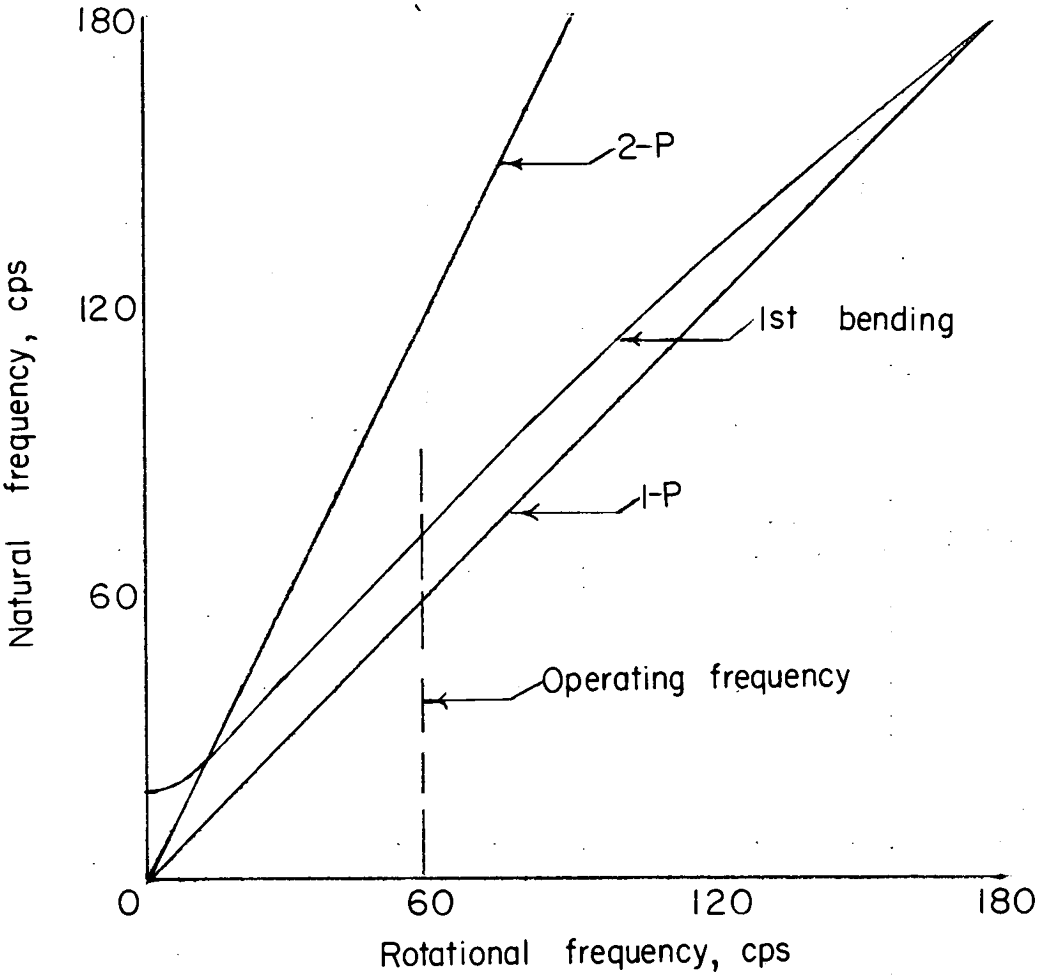

Figure 6.- Resonance diagram for supersonic propeller.

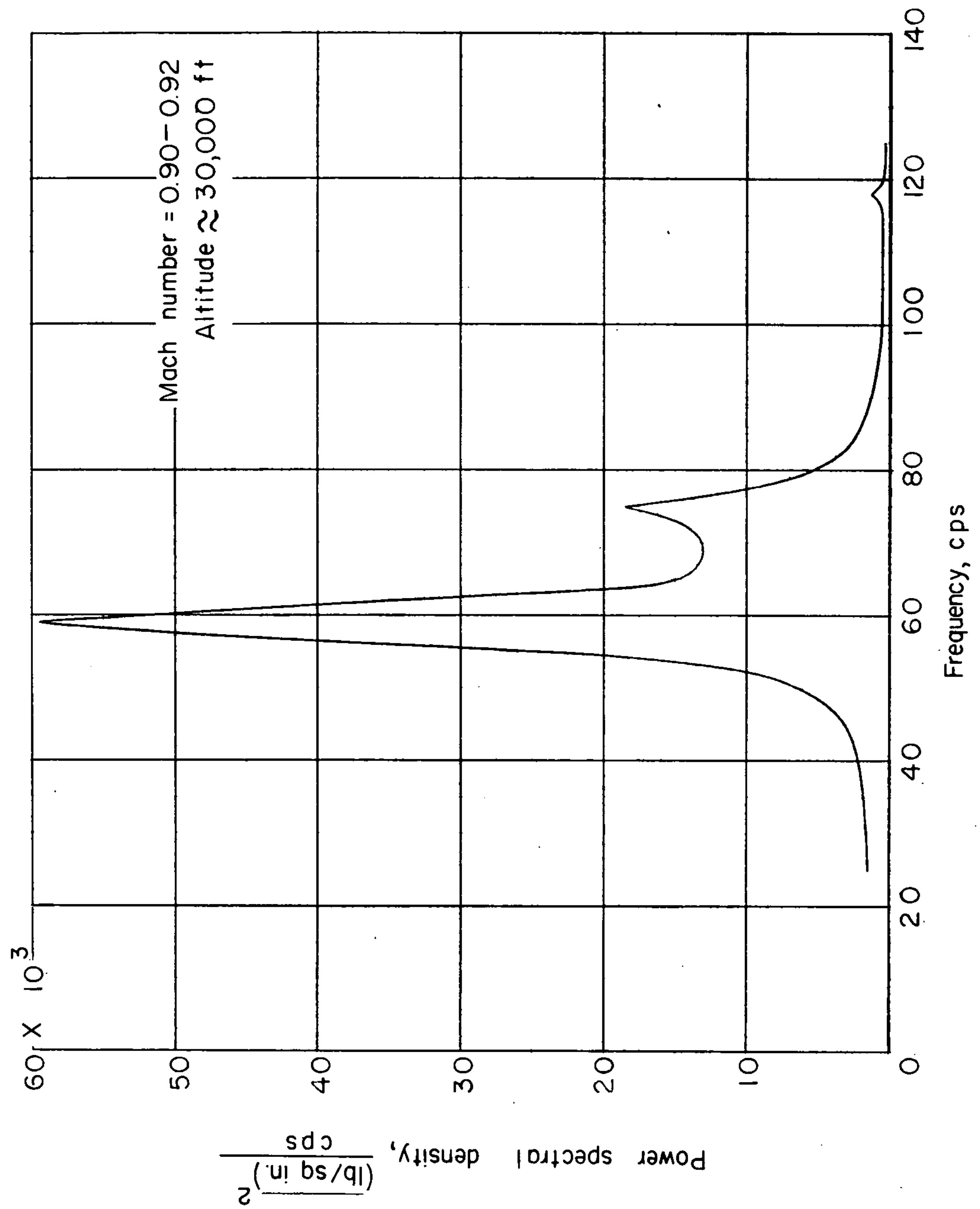

Figure 7.- Power spectral density of the vibratory bending stress at Mach numbers from 0.90 to 0.92.

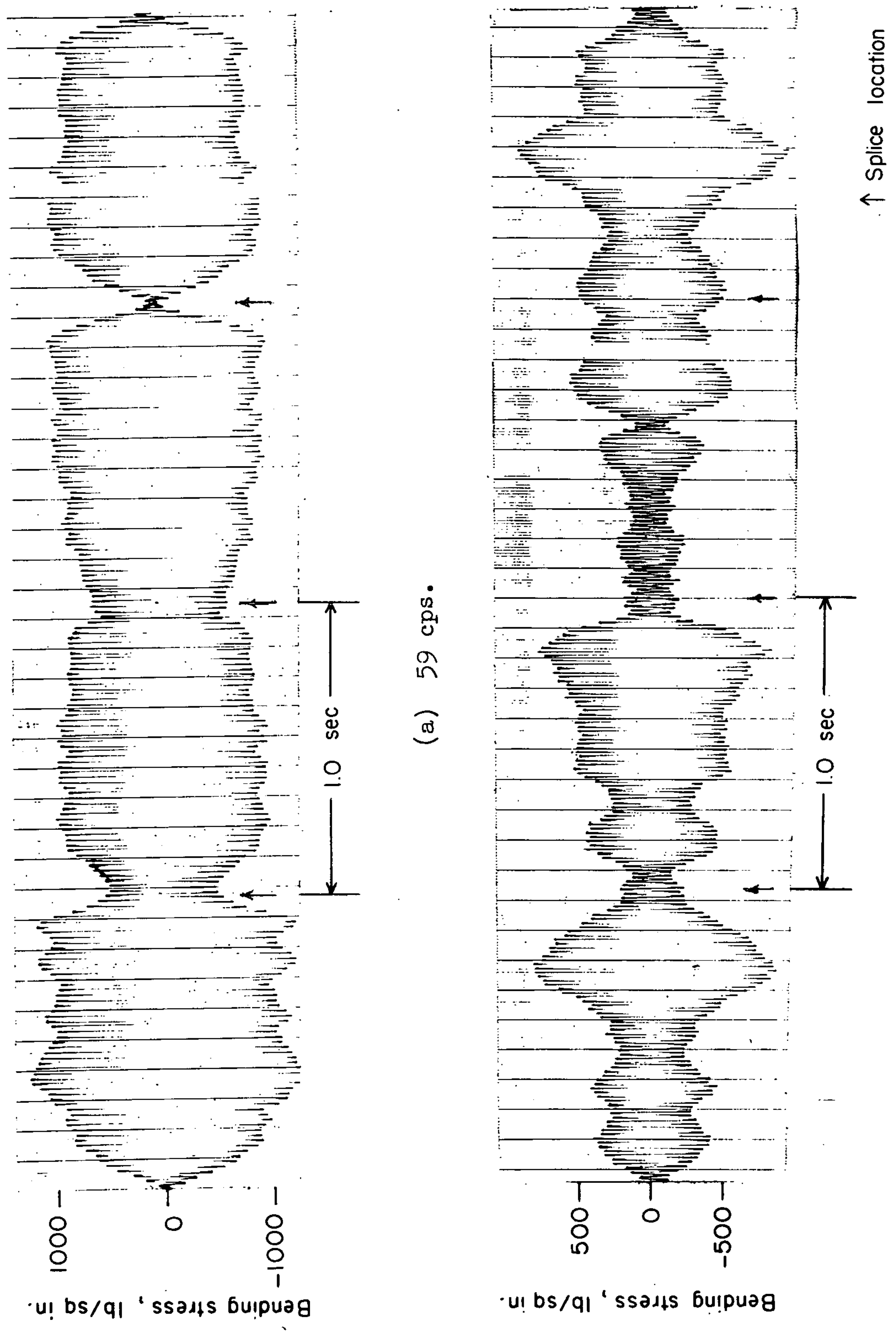

Figure 8.- Amplitude time history of vibratory bending stress at 59 and 75 cps for Mach numbers from 0.90 to 0.92.

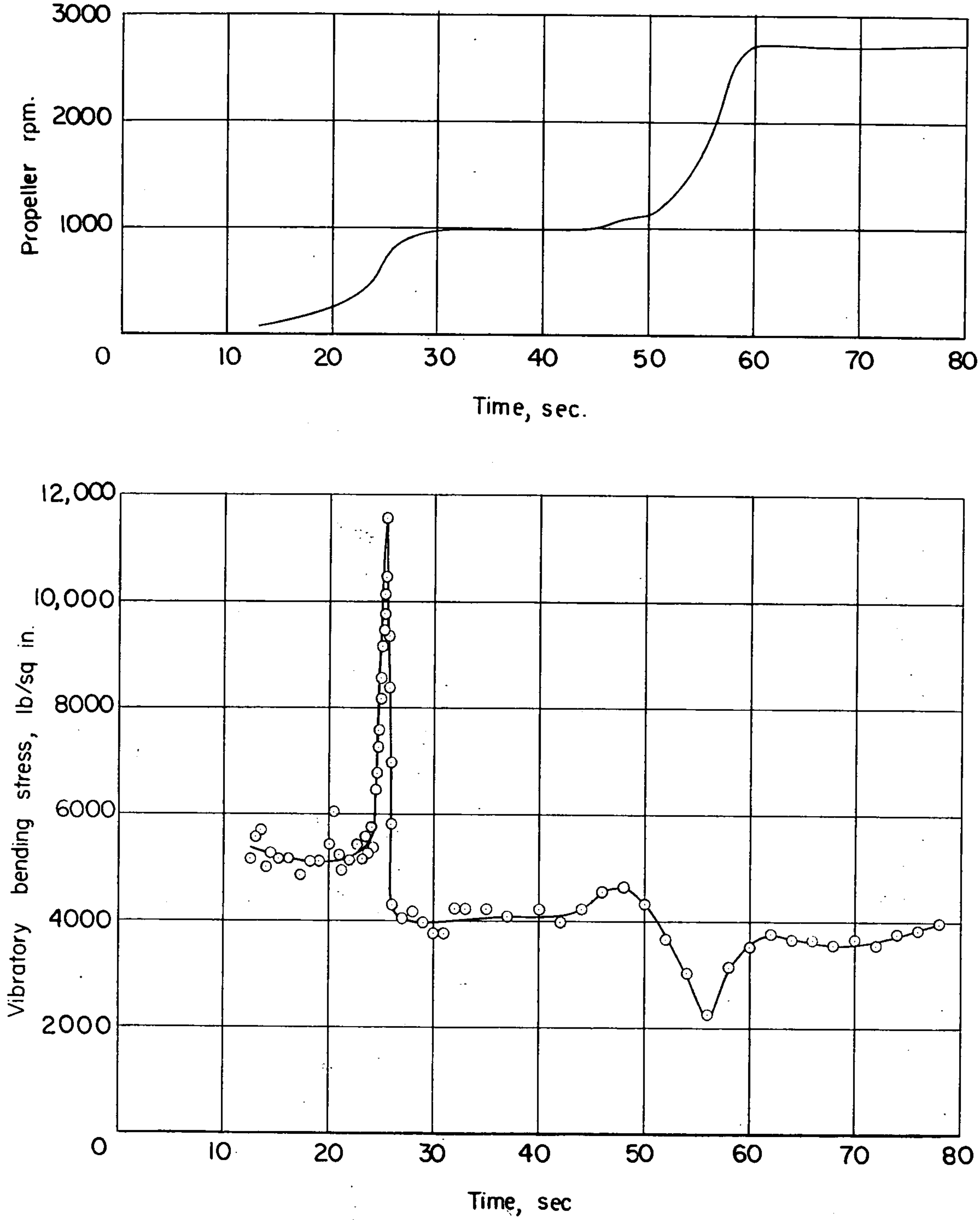

Figure 9.- Time history of maximum vibratory bending stress and rotational speed during an air start of turbine propeller combination.

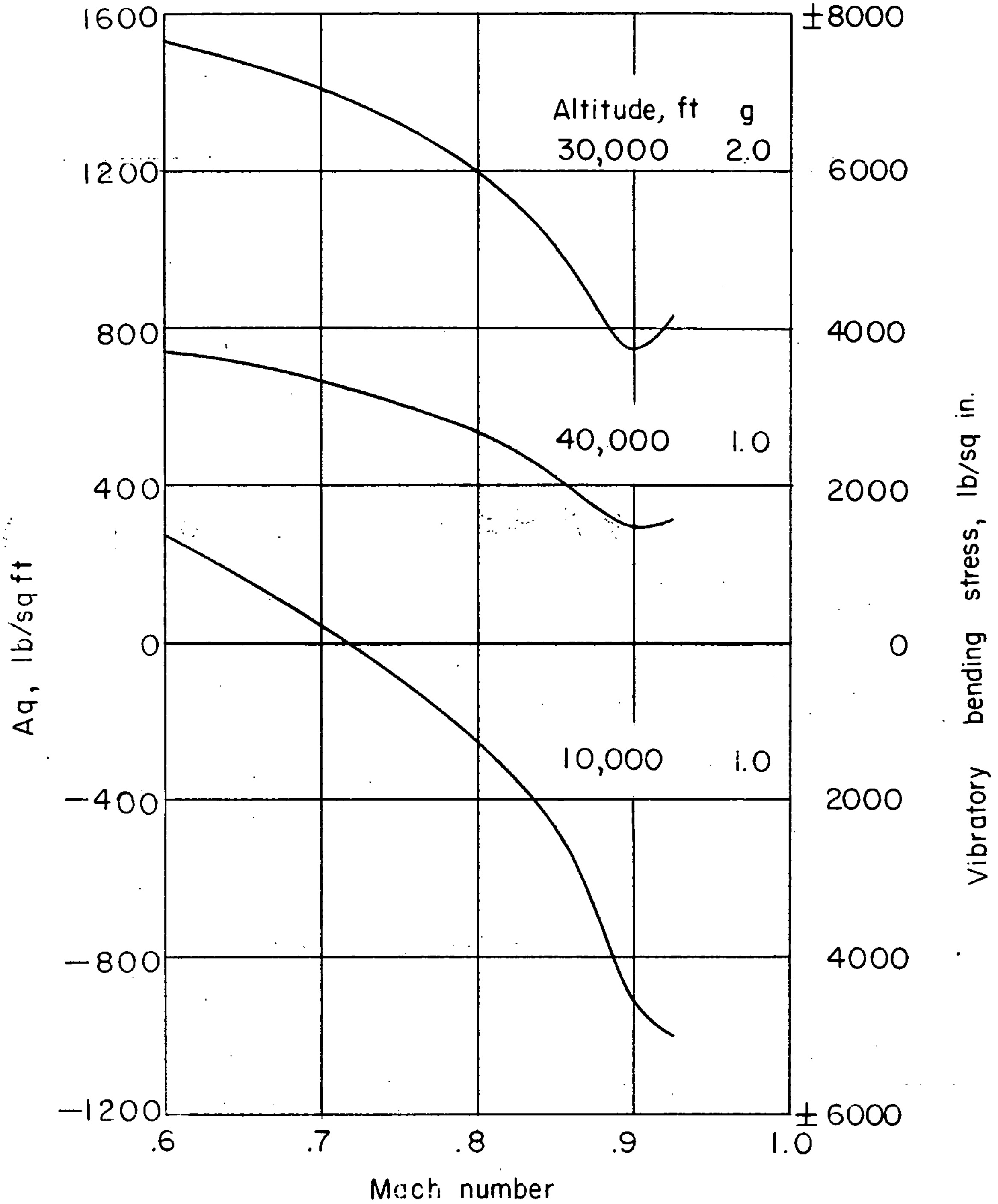

Figure 10.- Estimated 1-P stress and Aq factor for flight range of test airplane.

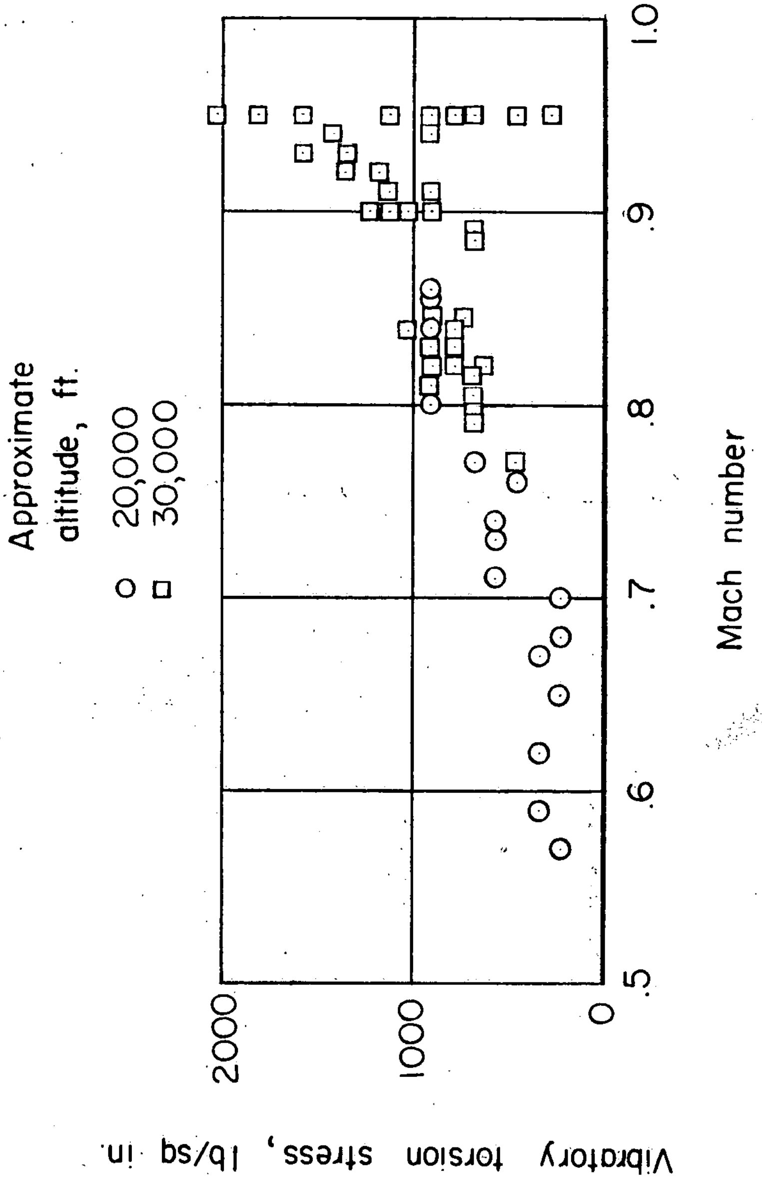

Figure 11.- Vibratory torsion stress for Mach numbers from 0.60 to 0.95.